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THE TRANSITION AND DYNAMICS OF BOUNDED AND FREE SHEAR LAYERS.(U)
MAR 82 J LAUFER, R KAPLAN, C HO   F49620-78-C-0060

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research activities in transitional and turbulent boundary layers and free shear flows between April 1978 and May 1982 are described. Experimental efforts which focused on an understanding of turbulent "spots" in a developing laminar boundary layer flow, the development of conditional sampling technique for high response anemometry data, studies of spanwise streaks in the near wall region of a turbulent boundary layer and the dynamics of free and impinging jet flows are described. Analytical studies of the nonlinear stability of plane stagnation flows are also discussed.

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FINAL REPORT

THE TRANSITION AND DYNAMICS OF BOUNDED AND FREE

SHEAR LAYERS

April 1, 1978-March 31, 1982
F49620-78-C-0060

Principal Investigators

John Laufer
Richard Kaplan
Ho, Chih-Ming

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I. Introduction

Our research activity during this funding period is reflecting our continued effort to explore further, the methods of detection generation and interaction of coherent structures in bounded and free shear layers. This line of research is based on the hypothesis that the key to the turbulent transport problem lies in a better understanding of the deterministic (rather than stochastic) features of the flow. This is in sharp contrast with experimental research of the past when one was interested mainly in the spatial distribution of some mean statistical quantities, such as the turbulent Reynolds stresses, without paying much attention to the temporal development of the flow generating these stresses. This time-dependent behavior, that could be regarded as the evolution of a secondary flow superimposed on the laminar-like primary one, is usually associated with the deterministic or large scale structures. There is more and more evidence that these structures are, in fact, either generated by, or are under the action of a previously occurring or a local instability mechanism.

If one accepts these general ideas then it is quite clear that at least some non-stationary aspect of the problem has to be retained in dealing with the problem. This imposes at least two difficult requirements on the experimental study of these flows. First, conventional time-averaged measurements are no longer sufficient; one has to devise more appropriate statistical methods to characterize the flow field. This involves pattern recognition techniques, conditional ensemble averaging methods among others that are still under development. In fact, Section

II-1 of this report describes our continuing efforts to develop and improve these techniques in a boundary layer. Second, one has to develop methods and types of measurements that would reveal whether or not some type of instability could explain the particular flow behavior. Part of the difficulty stems from the fact that very little theoretical guidance exists here. One has to rely on some very general instability characteristics, such as a wave like behavior (see Section II-2) or look for a Reynolds number effect (Sections II-3 and II-4).

In the early development of free shear layers the detection scheme is not a problem: one can use phase averaging to a great advantage in order to analyze the near field of an impinging jet (Section III-1) or to study the separation zone of the shear layer following the impingement (Section III-2). By understanding better the nature of the initial instability, more accurate measurements of the spreading rate can be accomplished (Section III-3) and the effect of a solid surface on the spreading rate more rationally evaluated (Section III-4).

II. Boundary Layer Flows

II-1) Estimation of "Large-Scale Structure" and "Turbulent Fluctuations" (R.E. Kaplan, J. Haritonidis)

The discovery of the "large scale" structure of a turbulent flow was initially measured with the technique of conditional sampling, which is analogous to triggering a signal averaging device on some feature of the turbulence, and summing the phase locked realizations. Flow visualization suggests that there are different sequences of turbulent events which can be observed, and it would be useful to compare the visual observations to the quantitative measurement whenever possible. Similar techniques have been applied to the turbulent spot, and the results suggest an "average picture" of the spot which has been subject to extensive investigations over the past five years, using the same techniques as were used in the turbulent boundary layer, but with a slightly more controllable environment (since the turbulence has boundaries which give more focus to the attention than continuous turbulence).

In most previous research, the conditional averaging techniques have neglected much of the phase information with the undesirable result that the constituent eddy structures are not sharply defined and are often lost completely amidst the averaged background. With a continuing desire to improve conditional averaging techniques, three different techniques have been tried to perform the separation of the constituents in our facility, all meeting with varying degrees of success. The aim of our separation is to preserve as much of the relative phase information as possible, since it is the small phases differences which contribute to the generation of turbulent kinetic energy.

a) The first approach used the "average" structure as an estimate. The Fourier transform of this average was taken as a pattern, and its spectral amplitude was stored for each frequency component. An individual realization of the turbulentce was then "Fourier transformed" and the phase of each Fourier component was extracted, which when combined with the amplitude of the "pattern" formed a Fourier transform with the <u>spectrum</u> of the pattern and the <u>phase</u> of the individual realization. Since the pattern has a broad spectrum, the division into "coherent-incoherent" parts is not done in an arbitrary manner in the frequency domain. However, the concept that the coherent part of a realization has the same spectrum as the pattern is as arbitrary as saying that it should have exactly the same form.

b) The second approach we have dubbed "peak-picking", and is performed as follows. Each individual realization is inspected point by point, and whenever a local maximum or minimum aplitude is detected, a data point is entered as the <u>average</u> value of the maximum and minimum at the time midway between the two times. The resultant "signal" then is defined at relatively few points over the interval of interest, and was then interpolated by a four or five point Lagrangian interpolated formula to yield a "smoother" representation of the "mean" of the signal. The technique (when applied twice) gave excellent agreement with the "line" one would draw through the data by eye (using the interpolation of the human brain). While this technique was very effective in separating the "estimated" structure (still with a degree of arbitrariness regarding the interpolation and stopping at two passes) it yielded a trace very close to what experienced observers would themselves select, and it performed the separation of components both of which are broad in frequency. Unfortunately, the scheme was so computationally demanding to make it impractical for calculation on the mini-computer and did not lend itself to easy conversion to the array processor.

c) The third scheme (still under development) is an extension of the second which is better suited to the talents of the array processor. Again, peaks and valleys of the signal are identified, however they are used to draw "linearly" interpolated envelopes of the signal (one for the peaks and one for the valleys). These envelopes lie outside of the bounds of the individual realization, but their average is a piecewise linear representation which has breaks at the location of <u>every</u> extremetry in the input signal. The algorithm used has the provision for declaring the relative "size" of the extremity (which is analogous to the two passes through the technique described under (2) above). The advantage of the scheme is its computational speed, as well as its splitting the signal immediately to one which has a reasonable fluctuation distribution.

These techniques are being pursued further and their utility is still to be determined. One goal is to determine if there is a "phase" relationship between the "lows" (or the estimate of the large scale structure) and the envelope of "highs" or the turbulent part. However, it must be emphasized that both the lows and the highs are spectrally broad and that both have the same degree of randomness as the original signal. It is clear that this decomposition can be done both in the turbulent spot and the turbulent boundary layer, and are used to isolate those energetic events which are responsible for turbulent drag.

II-2) Search for Wave-Like Behavior (R.E. Kaplan, J. Haritonidis, J. Laufer)

An experiment was performed to deduce whether there are "wave like" constitutents of wall turbulent flows. Five hot wires arrayed in a plane at a fixed elevation from the wall roughly in the shape of a "W" were digitally sampled, Fourier analyzed, and the resultant phases of the Fourier components were used to infer an "apparent wave number" for representative frequencies of interest. Two wave numbers were estimated from three wires, and a "wave structure" was detected when the two estimates were within ten percent. Four "flow" situations were studied: 1) the laminar wave packet following a turbulent spot, 2) the interior of a turbulent spot, 3) the wall region of a turbulent boundary layer, and 4) a completely random set of numbers.

Waves were detected only in the laminar region aft of a turbulent spot, and have been reported on previously. The other flows showed no evidence of waves according to this definition. The experiment was designed to emphasize those boundary layer elevations where waves are easily detected. However, the experiment suffered from several deficiencies. The major defect is the use of the streamwise velocity fluctuation (u') as the measured quantity (it would have been preferable to use the normal fluctuation (v') since is is not contaminated with non wave-like modes). The geometry of the probes was such that the cross stream extent was twice that of the streamwise extent (about 1.5 mm), so that structures that have a smaller streamwise coherence than about 3-4 mm could not be sampled. The streamwise coherence of all of the measured waves extended well beyond 20 mm, with isolated cases with wave lengths on the order of 50 mm.

The experiment had the negative conclusion that if wave-like structures exist in the wall region of these turbulent flows, they are so long and narrow that the technique used could not identify them.

II-3) Study of the Spanwise "Streaks" in a Turbulent Boundary Layer (J. Haritonidis, R.F. Blackwelder)

The so called "low speed streaks" observed in the wall region of bounded turbulent shear flows were studied extensively using rakes of twelve hot-wires in the spanwise direction. The simultaneous signals from the twelve sensors were analyzed using three principle techniques. Initially periodicity in the spanwise direction was sought using regular Fourier transform and cross-correlation techniques. A more detailed computational technique was developed, called the "maximum entropy" spectrum analysis method, which has been utilized primarily by geophysicists. This novel technique is most efficient in extracting nearly periodic information from random data without making any assumption about the nature of the data outside the observed window. Thirdly, maps of iso-velocity contours were constructed to form a visual impression of our data to be compared with other data.

The primary goal of this research was to establish the dependence of the streak spacing upon the Reynolds number. Since the nondimensional scale of the rake changed with the Reynolds number, three different rakes were constructed to study this effect. Data was taken over the range of $10^3 < Re_\theta < 10^4$ in a fully developed turbulent boundary layer. The probability distribution of the measured streak spacing is highly skewed having a most probable spacing at 80 ν/u_τ and an average value of 100 ν/u_t. These averages and the general shape of the distribution seemed to be independent of the Reynolds number.

II-4) Dependence of the "Bursting" Frequency upon Reynolds Numbers (R.F. Blackwelder and J. Haritonidis)

The average frequency of appearance of the turbulent producing eddies within bounded shear flows has been called the "bursting" frequency. This frequency has been measured by many investigators using a wide variety of techniques ranging from purely visual to complicated computer pattern recognition techniques. In spite of its importance to the structure of the wall layer turbulence, no reliable measurements of this parameter over a range of Reynolds numbers were available to determine if it should scale with the outer or inner variables in the shear flow.

A set of hot-wires were constructed which maintained a similar non-dimensional size in the wall region of the boundary layer over the range $10^3 < Re_\theta < 10^4$. The burst detecting scheme developed at USC earlier was used over the entire range to detect the bursting frequency. When scaled with the kinematic viscosity and the friction velocity, the nondimensional bursting frequency had a constant value of 0.003 over the entire range, thus indicating it is truly dependent upon the wall layer alone.

A corollary to this result was that the detection of the bursting frequency had a strong dependence upon the size of the hot-wire sensor. For wire lengths greater than twenty wall units, the sensor was sufficiently large that it apparently missed some of the bursts. That is, some of the bursts must have effected only a portion of the sensor causing a small undetected signal. This analomous effect complemented some earlier results in the literature which indicated the spanwise structure was very narrow.

II-5) <u>Nonlinear Stability of Plane Stagnation Flows</u> (P. Huerre & M.J. Lyell)

A Galerkin analysis of the linear and nonlinear stability of Hiemenz viscous stagnation flow has been carried out by expanding the fluctuation variables (velocity, vorticity, etc...) in terms of the family of modes pertaining to potential stagnation flow. We have shown that the three-dimensional linear stability of potential stagnation flow can be studied analytically, thereby revealing the complete structure of the linear stability of Hiemenz flow. It has been established that the Hiemenz flow is linearly stable, all its eigenvalues being damped. The modal disturbances can be interpreted as streamwise vortices which are superposed one on top of each other as one departs from the wall, the number of vortices being related to the order of the mode. We have also examined the stability of Hiemenz flow to finite amplitude disturbances. Truncated sets of nonlinear amplitude equations describing the evolution of a few modes (typically 3 or 5) have been analysed. These models imply that there exists a threshold surface in the phase space of modal amplitudes, which separates nonlinearly stable and unstable initial states. Viscous stagnation flow is therefore unstable to finite-amplitude disturbances, a feature which is in qualitative agreement with experimental observations.

III. Turbulent Jets

III-1) Dynamics of an Impinging Jet (Ho, Chih-Ming and Nosseir, Nagy S.)

In a high-speed subsonic jet impinging on a flat plate, the surface pressure fluctuations have a broad spectrum due to the turbulent nature of the high-Reynolds-number jet. However, these pressure fluctuations dramatically change their pattern into almost periodic waves, if the plate is placed close to the nozzle ($x_o/d < 7.5$). In the present study, extensive measurements of the near-field pressure provide solid support for the hypothesis that a feedback mechanism is responsible for the sudden change observed in the pressure fluctuations at the onset of resonance. The feedback loop consists of two elements: the downstream-convected coherent structures and upstream-propagating pressure waves generated by the impingement of the coherent structures on the plate. The upstream-propagating waves and the coherent structures are phase-locked at the nozzle exit. The upstream-propagating waves excite the thin shear layer near the nozzle lip and produce periodic coherent structures. The period is determined by the convection speed of the coherent structures, the speed of the upstream-propagating waves as well as the distance between the nozzle and the plate. An instability process, herein referred to as the 'collective interaction', was found to be critical in closing the feedback loop near the nozzle lip.

The aerodynamic noise generated by the impinging jet is studied from measurements of near field and surface pressure fluctuations. The far field noise measured at 90° to the jet axis is found to be generated by two different physical mechanisms. One mechanism is the impinging of the large coherent structures on the plate, and the other is associated with the initial instability of the shear layer. These two sources of noise radiate to the far field via different acoustical paths.

III-2) Unsteady Separation in an Impinging Shear Layer (Norbert Didden, Ho, Chih-Ming)

An axisymmetric jet (d = 1.5") impinges on a flat plate located at x/d = 4. The jet is forced by a loudspeaker at 70 Hz. The coherent structures will induce a secondary vortex near the wall and make the flow separate unsteadily.

The purposes of this experiment are to provide well documented data of an unsteady separated flow and to understand the physical mechanism of the unsteady separation.

The phase-averaged streamwise and transverse velocity components are measured at about three hundred stations distributed around the separated region. The mean surface pressure and the phase-averaged pressure fluctuations are also measured. The mean velocity, phase-average velocity profile, vorticity contour, strain rate contour, mean pressure gradient, and phase-average pressure gradient are processed from the measured data.

A very clear ejection of vorticity from the wall is observed near r/d = 1.1 and at about 10% phase advance from the passage of the primary vortex. A very large unsteady adverse pressure gradient occurs in front of the separation and appears ahead of time.

The passing primary vortex produces an adverse pressure gradient ahead of the vortex. The flow is retarded due to the adverse pressure gradient and is finally, separated from the wall. The favorable pressure gradient behind the primary vortex makes the flow reattach itself to the wall and forms a periodic separated flow.

The zero strain rate contour does not move with the convection speed of the primary vortex. Hence, the MRS criterion cannot be found in this unsteadily separated flow.

III-3) On the Preferred Modes and Spreading Rates of Jets (Ephraim Gutmark & Ho, Chih-Ming)

The measured preferred modes and spreading rates in individual facilities vary within a range of about 100%. This problem was discovered more than a decade ago, but no clue of what causes it is available up to the present time.

The present work suggests that extremely low level spatially coherent disturbances can change the initial conditions of a laminar shear layer. The downstream evolution of the coherent structures are consequently modified. The low level forcing localizes the vortex merging. The passage frequency measured at the end of the potential core can have a factor of two variations because the vortex could experience merging at a certain velocity. Therefore, the reported preferred modes are scattered.

Due to the externally imposed forcing, the initial Strouhal number will not remain constant while velocity may vary. We have shown that the spreading rate can be scaled with the initial Strouhal number. In the present measurement, the scaling law, as well as the accuracy of the constant used in predicting it have been demonstrated.

III-4) <u>The Development of the Shear Layer in a Lip Jet</u> (Hsaio, Fei-Bien & Ho, Chih-Ming)

In the separated flow, the interaction between a "free" shear layer and a solid boundary is always present. The purpose of this experiment is to examine the influence of the wall on the development of the free shear layer.

The experimental configuration is a two dimensional jet (1"x24") with a lip extension. The three lengths of lip extensions used are U/d = 2, 5 and 10, where D is the width of the nozzle and D = 1".

The initial instability frequencies measured at the shear layer without the lip extension are found to be independent of the lengths of the extensions (Fig. 1). However, the initial instability frequencies of of the shear layer with the lip extension are the same as the local vortex passage frequency of the other shear layer across the potential core.

The evolution of the coherent structures as a function of streamwise distance is examined from the passage frequency. The amplification of the subharmonic indicates the merging of two vortices. In the case of a free jet (Fig. 2), when the jet exit speed is 60 ft/sec, the subharmonic becomes detectable at $x/D \gtrsim 1$ but appears much further upstream ($x/D \approx 0.8$) in a lip jet (Fig. 3). In other words, the effect of the wall on the free shear layer becomes progressively important.

The passage frequencies at the end of the potential core ($x/d \simeq 5$) are measured at four different test cases (Fig. 4). When the lip extension is much shorter than the length of the potential core (e.g. the case of

L/D = 2), the passage frequencies are the same as those of a free jet. The Strouhal number, frequently referred to as the preferred mode, is about 0.24 (see the lower right corner of Fig. 4). When the lip extension is equal to or longer than the length of the potential core, L/D = 5, 10, the value of the preferred mode is significantly modified. The difference of the mean velocity profiles at x/D = 5 could be the main reason for the change in the passage frequencies.

From these preliminary results, it is clear that the presence of the solid boundary do have an effect on the development of the "free" shear layer. Further studies could lead to more understanding of the interaction between a shear layer and a wall e.g. in a separated flow.

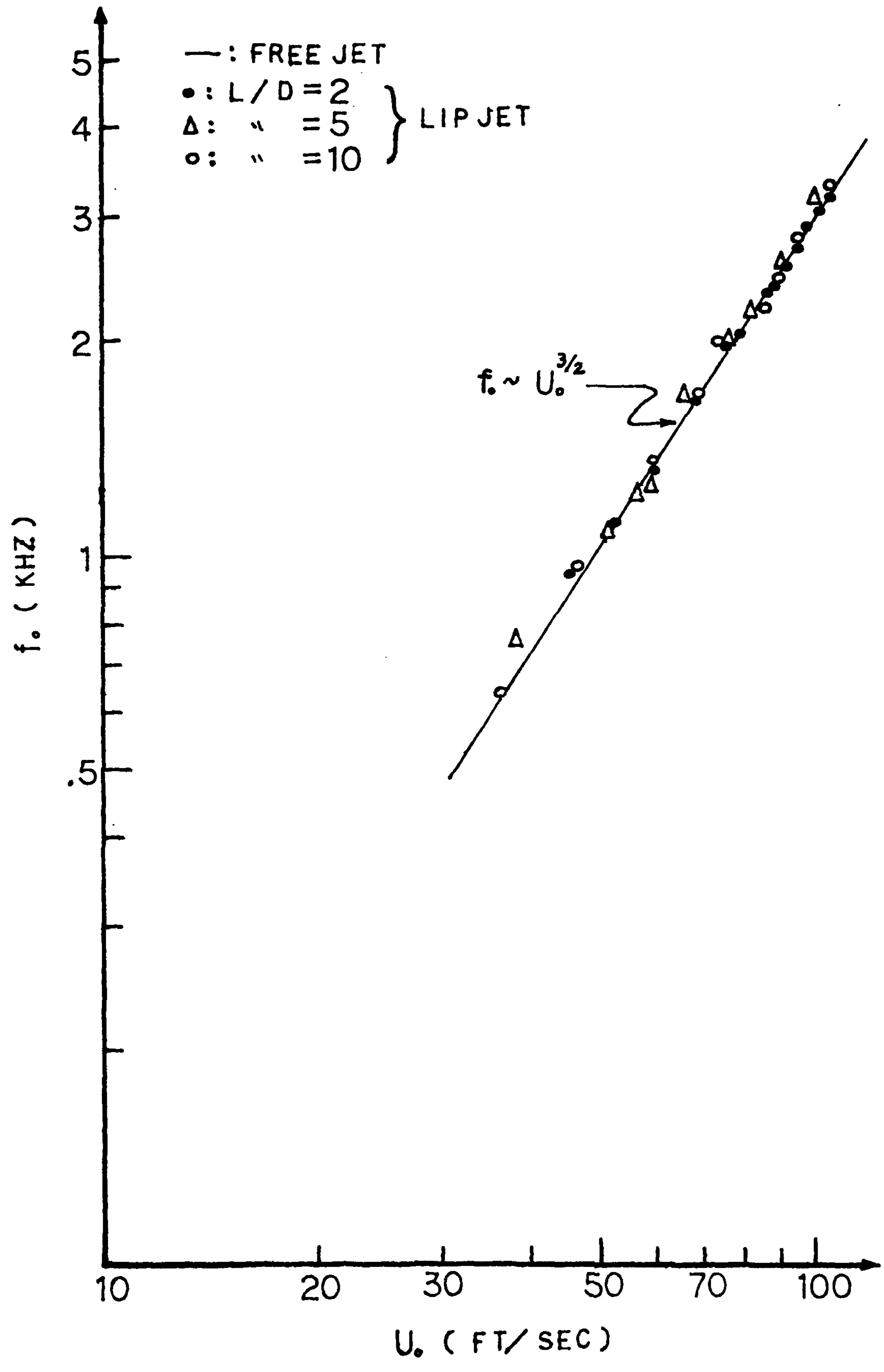

Figure 1. Initial instability frequencies

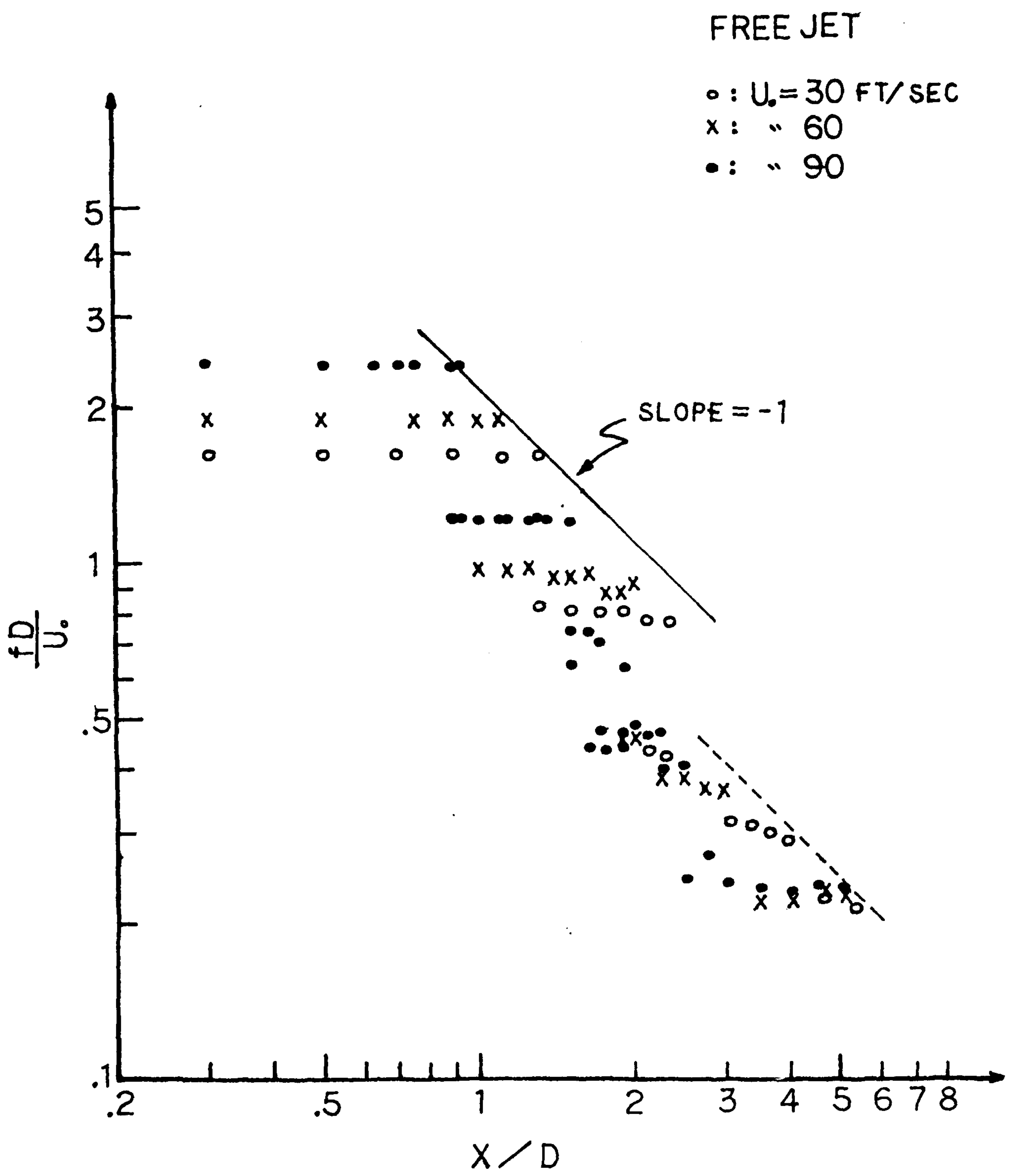

Figure 2. Vortex passage frequency as a function of streamwise distance (free jet).

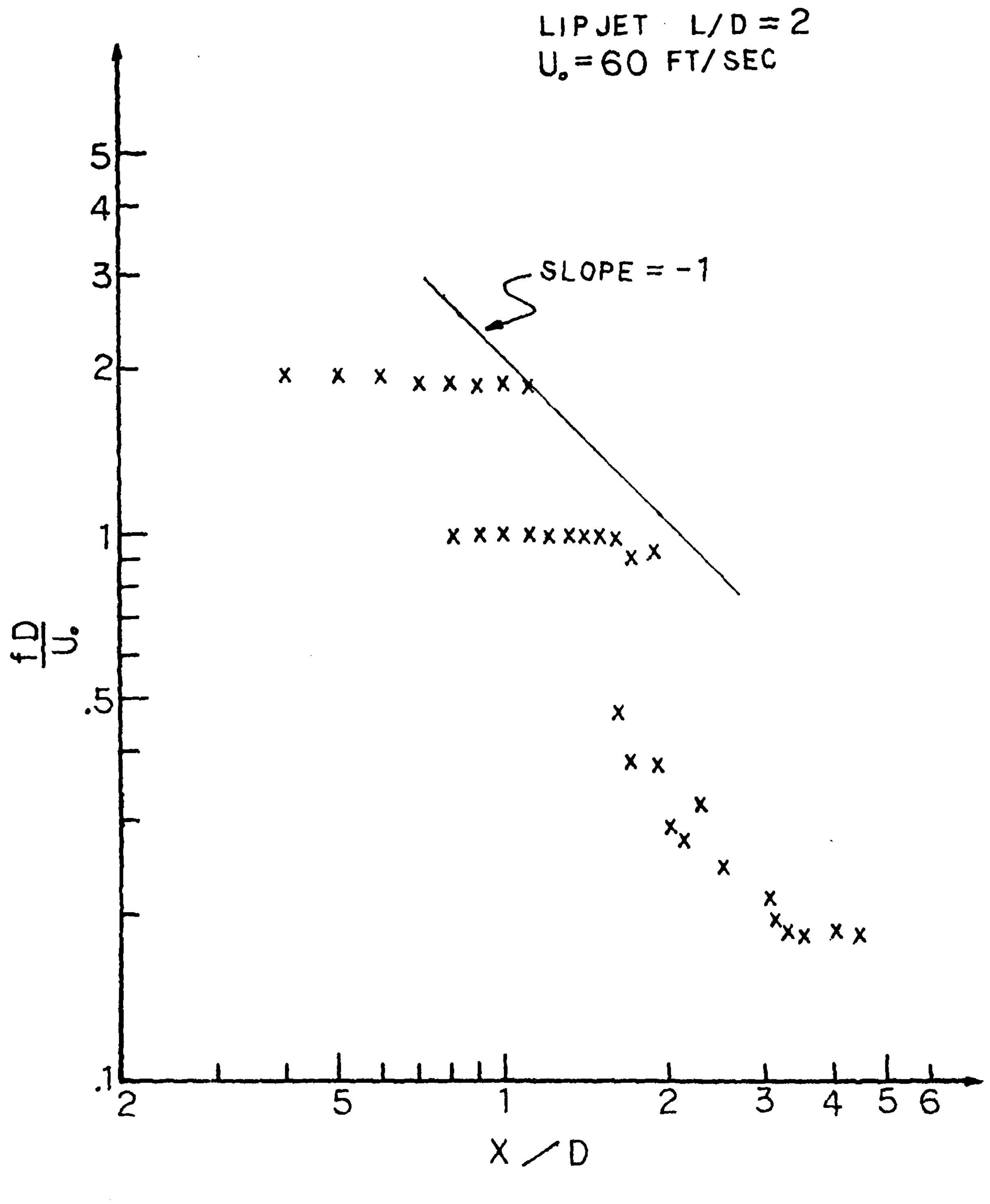

Figure 3. Vortex passage frequency as a function of streamwise distance (lip jet).

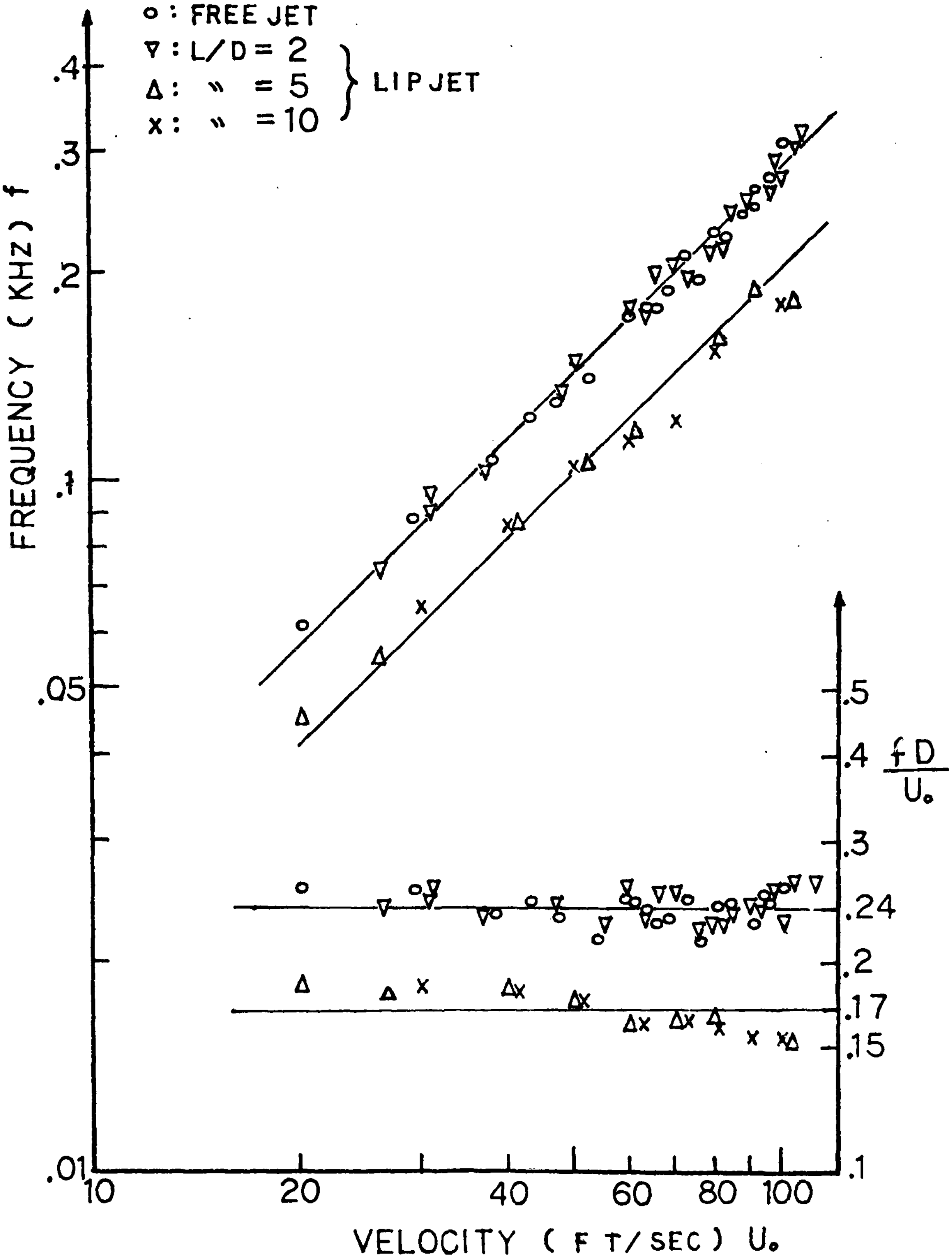

Figure 4. Preferred modes of free jet and lip jet.

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1. "Stability of Plane Stagnation Flow", by Lyell, M.J. and Huerre, P., Bulletin American Physical Society, vol. 26, p. 1285, 1981.

2. "Detection of Waves in Turbulent Flows", by Kaplan, R.E., Haritonidis, J.H. and Blackwelder, R.F., Bulletin American Physical Society, vol. 25, p. 1103, 1980.

3. "Instability of Stagnation Flow Against a Curved Plate", by Lyell, M.J. and Huerre, P., Bulletin American Physical Society, vol. 25, p. 1081, 1980.

4. "The Relation Between Sub-Layer Streaks and Spot Streaks", by Haritonidis, J.H., Bulletin American Physical Society, vol. 25, p. 1102, 1980.

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6. "Reynolds Number Dependence of the Bursting Frequency in Turbulent Boundary Layers", by Blackwelder, R.F. and Haritonidis, J.H., Bulletin American Physical Society, vol. 25, p. 1094, 1980.

7. "On the Spreading of a Turbulent Spot in Absence of Pressure Gradient", by Wygnanski, I.,Haritonidis, J.H. and Zilberman, J., accepted for publication in JFM, August, 1980.

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16. "The Bursting Frequency in Turbulent Boundary Layers", by Blackwelder, R.F. (accepted for publication in JFM), 1981.

Ph.D. Degree Awarded

Haritonidis, Joseph H., June 1978.

Personnel

Laufer, J. - Professor
Principal investigator

Kaplan, R. - Professor
Co-Principal Investigator

Blackwelder, R. - Professor
Sr. Investigator

Huerre, P. - Assistant Professor
Sr. Investigator

Redekopp, L. - Professor
Sr. Investigator

Haritonidis, J. - Research Associate: 1978 - 1981

Monkewitz, P. - Research Associate: 1979

Motohashi, T. - Research Associate: 1981 - 1982

Rogler, H. - Sr. Research Associate: 1978

Bental, O. - Research Scholar: 1978 - 1979

Xiaokuan, Z. - Research Scholar: 1981 - 1982

Plocher, D. - Research Engineer: 1979 - 1982

Kuo, C.T. - Graduate Student: 1978 - 1979

Lee, I. - Graduate Student: 1980

Lyell, M. - Graduate Student: 1979 - 1982

Williams, R. - Graduate Student: 1980

Young, W. - Graduate Student: 1979 - 1980

Publications

"The Instability of Plane Stagnation Flow", Huerre, P., Lyell, M.J. & Blackwelder, R.F., 32nd Meeting of the American Physical Society, Division of Fluid Dynamics, November 1979.

"Instability of Stagnation Flow Against a Curved Plate", Lyell, M.J. & Huerre, P., 33rd Meeting of the American Physical Society, Division of Fluid Dynamics, November 1980.

"Stability of Plane Stagnation Flow", Lyell, M.J. & Huerre, P., 34th Meeting of the American Physical Society, Division of Fluid Dynamics, November 1981.

Ph.D. Student

M.J. Lyell, scheduled to finish her dissertation and graduate in Summer 1982.

Ph.D. Degree Awarded

Nosseir, N.S., August 1979
Thesis title: "On the Feedback Phenomenon and Noise Generation of an Impinging Jet".

Personnel

Ho, C.M. - Associate Professor
Principal Investigator

Nosseir, N.S. - Graduate Student: 1975-1979
Research Associate: 1979-1980

Didden, N. - Research Associate: 1980-1982

Gutmark, E. - Consultant: 1980 (summer)
Research Scientist: 1981-1982

Hsaio, F.B. - Graduate Student 1979

Publication List

1. "Dynamics of an Impinging Jet Part I: The Feedback Phenomenon", by Ho, C.M. and Nosseir, N.S., J. Fluid Mech., vol. 105, pp.110-142 (1981).

2. "Dynamics of an Impinging Jet Part 2: The Noise Generation", by Nosseir, N.S. and Ho, C.M., J. Fluid Mech., vol. 116, pp. 378-391 (1982).

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5. "The Role of Coherent Structures in an Impinging Jet", by Ho, C.M. and Nosseir, N.S., Bulletin of the American Physical Society, Ser. II, vol. 23, p. 1013 (1978).

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7. "Feedback Mechanism in a Free Jet", by Ho, C.M. and Gutmark E., Bulletin of the American Physical Society, vol. 25, p. 1102 (1980).

8. "Unsteady Separation in the Boundary Layer of an Impinging Jet" by Didden, N. and Ho, C.M., Bulletin of the American Physical Society. vol. 26, p. 1261 (1981).

9. "On the Preferred Modes and the Spreading Rates of Jets", by Gutmark, E. and Ho, C.M. (to be submitted).

10. "Unsteady Separation in an Impinging Shear Layer", by Didden, N. and Ho, C.M. (in preparation).